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13. ABSTRACT ***(Maximum 200 Words)***

We fabricated C/SiC laminates with layer thicknesses spanning two length scales: micro (μm) and nano (nm) and fabricated particle reinforced composites consisting of particles (cobalt and SiC) and polymer matrix (polysterene and epoxy) with particle diameters spanning these two scales. The laminates were made using laser vapor deposition technique, while particle reinforced composites were made using either polymer synthesis or resin transfer molding technique. Secondly, we characterized the ultrastructures of these composites using SEM and TEM, and measured their local and global properties using nanoindentation apparatus, DMA, and MTS testing equipment. The focus was on matrix-inclusion interface. Finally, we conducted modeling of such composites. It included the modeling using classical micromechanics approaches with account for ultrastructural features such as interphase thickness, reinforcement shape and voids, and generalized continuum modeling using couple stress theory. In addition we conducted a study of concentrated force problem using micromechanics based continuum theory. This should be useful in interpreting a nanoindentation data.

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A FINAL REPORT

for the project entitled

Nanolaminates and Microlaminates: Modeling and Characterization

Submitted to

AFOSR

by

Georgia Institute of Technology

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2. OBJECTIVES

The objective of this research was to develop micromechanics models of laminated and particle reinforced composite materials at different scales and to verify the models experimentally. This research should permit optimization of properties of ceramic/ceramic and metal/ceramic laminates and particle reinforced polymer matrix composites. This research involved the following:

- Macroscale laminate and particulate composites modeling using classical continuum mechanics theories and micromechanics,
- Microlaminate and microparticle reinforced composites modeling using non-classical theories, such as micropolar or strain gradient theories,
- Nanoscale laminate and nanoparticle composites modeling accounting for discrete microstructures of constituents,
- Fabrication of C/SiC and Re/SiC laminates with layer thickness spanning three length scales (mm, μm, nm); fabrication of particle reinforced composites consisting of cobalt particles and polymer matrix (polysterene, polyethelyne and rubber) with particle diameters spanning two scales: micro (μm) and nano (nm),
- Measurement of mechanical properties and characterization of microstructures of individual layers and laminates at all three length scales, and polymer matrix composites at two scales,
- Verification of analytical results with experimental measurements across length scales,

The first long term objective was to advance modeling of laminates at micron and nanoscales in order to permit the development of novel laminates possessing superior mechanical properties. Such materials are useful in structural and electronic aerospace applications. Such laminates were fabricated via laser-jet chemical vapor deposition (LCVD) method.

The second long term objective involved the advancement in modeling of particle reinforced polymer matrix composite materials with diameters of nanometer size and the development of processing techniques that yield composites with nanometer size reinforcement possessing superior properties. The interest was in identifying how properties are changed when reinforcement decreases to nanosize. Several types of polymer matrix were explored.

NOTE: The original proposal included the investigation of laminated systems (i.e. first objective) while in the second year we extended the research to include polymer matrix nanoparticle reinforced composites.

3. STATUS OF EFFORT

During the two-year duration of the project we addressed the following items:

- Fabrication of C/C and C/SiC laminates, and testing of local properties using nanoindentation technique. We have obtained a thorough understanding of the LCVD of carbon layers and have learned how to control the process so that carbon deposits can be made reproducibly. We also have improved our understanding of the LCVD of silicon carbide.

- Fabrication of nanoparticle reinforced polymer matrix composites. We made progress in making nanocomposites with polysterene matrix and cobalt particles and made nano- and microcomposites with epoxy matrix and SiC particles in collaboration with researchers at Turkagee University in Alabama. We also did testing of local properties of micro and nanolaminates using nanoindentation technique and measured macroscopic properties of particle reinforced composites.
- We modeled particle reinforced composites modeling using non-classical theories, more specifically couple stress theory. We developed the methodology to predict couple stress constants of composite materials with classical constituents.
- In addition we used a recently developed theory (Zubelewicz, 2001), capable of identifying cavitation mechanisms in power-law creeping materials. This is a continuum theory, which has a micromechanics-based flow rule. We solved the planar elasticity problem involving the concentrated force acting on a half-plane (Flamant problem). This problem is of importance in nanoindentation technique, which relies on measurement of local material properties using very small forces.

4. ACCOMPLISHMENTS/NEW FINDINGS

Our research highlights include fabricating C/SiC laminated samples and nanoparticle polymer matrix composites and modeling as discussed in item 3. This analysis and fabrication of laminated composite materials followed closely the goals set in our proposal. The investigation of nanoparticle polymer matrix composites was a new related topic which developed in the second year of the research project. Additional theory addressing the cavitation was also a new development, not proposed in the initial proposal and it was complementary to the non-classical continuum approaches. It is applicable to both polymers and metals.

5. PERSONNEL SUPPORTED

Two faculty members: Drs. Iwona Jasiuk and Jack Lackey were involved in this project. Five graduate students Jefferey Jordan, Dan Jean, Scott Bondi, Josh Gillespie, and Ryan Johnson were also supported from this grant.

6. PUBLICATIONS

The following papers were published:

M. Jiang, I. Jasiuk, and M. Ostoja-Starzewski (2002), "Apparent elastic and elastoplastic behavior of periodic composites," *International Journal of Solids and Structures*, **39**, 199-212.

F. Bouyge, S. Boccara, I. Jasiuk, and M. Ostoja-Starzewski (2002), "A Micromechanically Based Couple-Stress Model of an Elastic Orthotropic Two-phase Composite," *European Journal of Mechanics/A: Solids*, **21**, 465-481.

M. Jiang, I. Jasiuk and M. Ostoja-Starzewski (2002), "Apparent Thermal Conductivity of Periodic Two-dimensional Composites," *Computational Materials Science*, **25** (3), 329-338.

D. Jean, C. Duty, R. Johnson, S. Bondi, and W. J. Lackey (2002), "Carbon Fiber Growth Kinetics and Thermodynamics Using Temperature Controlled LCVD," *Carbon*, **40**(9), 1435-1445.

Ji Eun Park, I. Jasiuk and A. Zubelewicz (2003), "Micromechanics-Based Interfacial Stress Analysis and Fracture in Electronic Packaging Assemblies," *ASME Journal of Electronic Packaging*, **125**, 44-52.

The following papers are in press:

I. Jasiuk and M. Ostoja-Starzewski (2003) "From Lattices and Composites to Micropolar Continua," in *Trends in Nanoscale Mechanics: Analysis of Nanostructured Materials and Multi-Scale Modeling*, V.A. Harik and D.A. Salas (Eds), Kluwer Publishers, in press (invited paper).

I. Jasiuk and M. Ostoja-Starzewski, "On the Reduction of Constants in Planar Cosserat Elasticity with Eigenstrains and Eigencurvatures," *Journal of Thermal Stresses,* in press.

Ji Eun Park, I. Jasiuk and A. Zubelewicz, "Interfacial Stress Analysis and Fracture in Electronic Packaging Assemblies with Heterogeneous Underfill," *ASME Journal of Electronic Packaging*, in press.

C. Duty, R. Johnson, J. Gillespie, A. Fedorov, and W. J. Lackey, "Heat and Mass Transfer Modeling of an Angled Gas-Jet LCVD System," *J. Applied Physics*, in press.

Ryan Johnson, Scott Bondi, Chad Duty, Daniel Jean, Tarek Elkhatib, and W. Jack Lackey, "Fabrication of Multi-Layered Carbon Structures Using LCVD," Twelfth Annual Solid Freeform Fabrication Symposium, University of Texas at Austin, 61-68, August, 2001.

Z. Kang, R. Johnson, S. Bondi, M.Jiang, J. Gillespie, and W.J. Lackey, "Microstructure of Carbon Films Prepared by LCVD," *Carbon,* submitted.

The following dissertations were published:

Daniel L. Jean , "Design and Operation of an Advanced Laser Chemical Vapor Deposition System with On-Line Control," Ph.D. Dissertation, Georgia Institute of Technology, August 2001.

Jefferey Jordan, "Composites at Micro- and Nano-Scale and a New Approach to the Problem of a Concentrated Force on a Half-Plane," M.S. Dissertation, Georgia Institute of Technology, May 2003.

Several other papers are in preparation:

J. Jordan, I. Jasiuk, R. Tannenbaum and K. Jacob, "Experimental Trends in Polymer-Matrix Nanocomposites - A Review," *Polymer*, to be submitted.

Jasiuk, J. Jordan, H. Mahfuz, "Epoxy Matrix Composites with Nano vs. Micron Sized SiC Particle Reinforcement," *Composites Science and Technology*, to be submitted.

A. Zubelewicz, J. Jordan and I. Jasiuk, "New Approach to a Concentrated Force in Half-Plane," *International Journal of Solids and Structures*, to be submitted.

7. INTERACTIONS/TRANSITIONS

a. participation in several conferences where nanotechnology and laminate structure papers were presented, several papers are submitted for presentation at national/international conferences

J. Jordan, I.Jasiuk, R. Tannenbaum, K. Jacob, M Sharaf, "Polymer matrix nanocomposites: Experiments and modeling," presented at the 2002 ASME International Mechanical Engineering Congress, New Orleans, LA, November, 2002.

b. collaboration with Dr. Aleksander Zubelewicz (since the beginning of the project)
c. collaboration with Dr. Aleksander Zubelewicz (since the beginning of the project)

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Nature of collaboration:

- Modeling of layered materials, developments of analytical models for layered systems. Determination of stresses in layered composites using analytical or computational approaches. Development of micromechanics-based fracture criterion at bi-material interfaces.

Applications: Reliability of MEMS. Design of reliable electronic packaging devices

- Solution of concentrated force problem including cavitation effects.

Applications: Interpretation of nanoindentation results.

8. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

9. HONORS/AWARDS

None.